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DESIGN AND PERFORMANCE OF A REAL-TIME SOLID PARTICLE COUNTING SYSTEM

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ABSTRACT
A solid particle counting system (SPCS) has been developed. It measures engine exhaust solid particle number emission in real-time. The instrument is designed to follow the recommendation of PMP draft regulation for number emission measurement on Light-duty diesel vehicles. Two wide range continuous diluters, which were developed in this project, have been used as cold and hot diluters, respectively. The accuracy of the dilution ratio is normally ± 2% in the designed range. The instrument has low particle losses and exhibits over 95% penetration for solid particles. The SPCS can measure transiently the particle emission from vehicles as well as from engines with and without catalyst.

Keywords: Solid particles, Diesel Engine, Exhaust Gas, Dilution Ratio, PMP, NEDC

1. INTRODUCTION
GRPE-PMP (Particle Measurement Program under the auspices of the UNECE) has proposed a draft regulation for light-duty diesel (LDD) vehicle exhaust particle number measurement [1]. It is recommended that soluble organic fraction (SOF) and sulfate particles be removed from the exhaust flow. The aerosol with solid particles only moves into the condensation particle counter (CPC), where the number concentration is measured. The minimum size for solid particles is at 23 ± 3 nm, and the maximum is in 2500-10000 nm. The constant volume sampler (CVS) is recommended to be the primary tunnel and the SPCS takes sample from the CVS. The draft regulation recommends the particle measurement system consist of sample probe and transfer line, pre-classifier, heat diluter (PND_1), evaporation tube (EU), cold diluter (PND_2), and particle counter. The sample probe and transfer line deliver sample flow to the pre-classifier. The pre-classifier provides 50% cutoff point for 2500 nm particles [2].

The hot diluter (PND_1) dilutes exhaust with particle free air. The dilution air temperature is heated at ≥150 ºC. High temperature dilution suppresses the formation of volatile particles in PND_1. The evaporation tube with the temperature of 300 to 400 ºC removes SOF and sulfur compound particles. By following the cold dilution with PND_2, concentrations of SOF and sulfur compound at gas phase are decreased to a lower concentration. As a result, the chance for gas phase SOF and sulfur compound re-nucleating to form particles is minimized [3s]. By cooling the heated sample from temperature over 300 ºC to room temperature quickly with PND_2, particle losses by thermophoresis are minimized as well. Finally, the concentration of the solid particle is counted in the condensation particle counter (CPC, TSI Model 3010D) with cutoff size 23nm, which is recommended by the PMP.

2. EXPERIMENTAL SYSTEM AND METHOD

2.1 SPCS System Description
Figure 1 shows flow schematic for the SPCS. The SPCS integrates the pre-classifier, the hot diluter (PND_1), evaporation tube (EU), the cold diluter (PND_2), condensation particle counter in a single system. A stainless steel cyclone is used as the pre-classifier. In order to make an easy operating instrument, data acquisition and control system were developed. Many functions, of which some are recommended by PMP such as particle measurement, zero checks for CPC and the system, flow check for CPC, and daily linearity check, data save, etc., were automated.

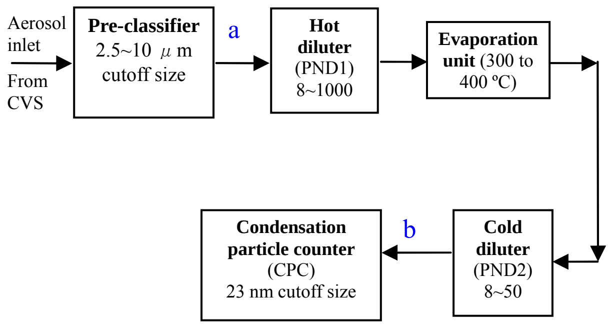

Fig 1. Block diagram of the SPCS

Figure 2 presents the main display window for the control software. The dilution ratios and dilution air flows for the hot (PND_1) and cold (PND_2) diluters can be controlled to expected values during running condition. Two PID loops were built in the software for hot diluter (PND_1) and cold diluter (PND_2), respectively. They control dilution ratios at set points while the back pressure and temperature change in CVS. Thus, the SPCS isn't sensitive to the sampling condition. The real-time dilution ratio and flow are with small variation (<±3%) during the steady-state operation.

Diluters have fast response at most of operation conditions. The CPC used has about 5-second (T_{90}) response time and it can measure transient concentration. Therefore, the SPCS is good for engine solid particle number measurement during steady-state and transient conditions.

Fig 2. Main screen for the SPCS control software

2.2 Wide Range Continuous Diluter

A wide range continuous diluter (WRCD) has been developed for the PND_1 and PND_2 to achieve the SPCS specification [4]. This diluter provides real-time dilution ratios, since the sample flow is measured in real-time. Dilution ratios are accurate over the whole dilution range. The new invented diluter consists of mass flow controllers, pressure transducers, thermocouples, vacuum source, orifice flow meters, mixer, and critical orifice. The schematic of the diluter is presented in Figure 3.

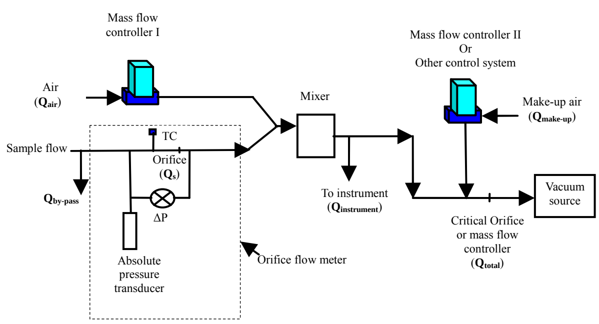

Fig 3. Schematic of the wide range continuous diluter

All flow rates leveled are at standard condition. $Q_{by-pass}$ is the by-pass flow upstream of the orifice. The function of the by-pass flow is to minimize the residence time of the sample flow. Q_{total} is the total mixture flow in the system. It is controlled as a constant by a critical orifice. Q_{air} is the particle free dilution air, and is controlled as constant by a mass flow controller. Q_s is the sample flow, and measured by the orifice flow meter in real-time. $Q_{make-up}$ is the make-up air flow. It can be adjusted, and the flow rate is controlled by mass flow controller. In the normal operation, it is much smaller than the dilution air flow. $Q_{instrument}$ is the flow into the instrument or filter. It can be either the constant or varied. The sample flow and the dilution air are mixed in a mixer. The mixer provides the uniform mixing of the sample flow and dilution air. The flow in the diluter can be defined as equation 1:

$$Q_{total}=Q_{air}+Q_s+Q_{make-up}-Q_{instrument} \quad (1)$$

As described above, the total flow and dilution air are maintained as constant during the operation. By adjusting the make-up air flow ($Q_{make-up}$), the total flow (Q_{total}) will keep as constant under all conditions. As a result, the sample flow (Q_s) is changed. The dilution ratio (DR) can be defined as:

$$DR= (1+Q_{air}/Q_s) \quad (2)$$

Since the dilution air flow is kept unchange, the dilution ratio is the function of the sample flow only. When the sample flow is increased with the decrease of the make-up flow, the dilution ratio is decreased. Since the make-up air is adjusted continuously, the sample flow is changed continuously. Therefore, the continuous dilution ratio is obtained. 1:1 of dilution ratio can be achieved without the dilution air flow (Q_{air}=0).

3. RESULTS AND DISCUSSION

3.1 Daily Linearity Check

PMP draft regulation suggests performing daily linearity of the CPC before testing vehicles. A daily calibration unit (DCU) has been developed at Horiba [5]. It provides variable concentration of aerosol for the calibration. From the range of 0 to 10000 particles/cc on TSI CPC 3010D, the calibration unit can provide over 20 constant concentrations for the linearity check. The constant concentration on the calibration unit is controlled by the SPCS computer.

In the DCU an atomizer generates the poly-disperse aerosol and a diffusion dryer removes water from the aerosol. Then the aerosol moves into an ejector diluter for dilution of which the dilution ratio is controlled by the SPCS computer. By inputting the expected percentage concentration (0 to 100%) from the computer, the aerosol diluter provides the expected concentration to the CPC. After one point has been completed, the software controls the aerosol diluter to provide the other concentration, which has been configured at the beginning of the calibration. In the mean time, the measured concentration is plotted on the SPCS computer screen. R-square value is calculated simultaneously.

Figure 4 shows the results for daily linearity check. The y-axis is the average concentration measured by the CPC. The x-axis is the reference concentration obtained from equation 1.

$$C = C_{raw}/DR = C_{raw}*P \quad (3)$$

Where, C is the reference concentration; C_{Raw} is the raw concentration into the aerosol diluter, and measured by the same CPC; DR is the dilution ratio on the aerosol diluter; and P is the percentage concentration from 0 to 100%.

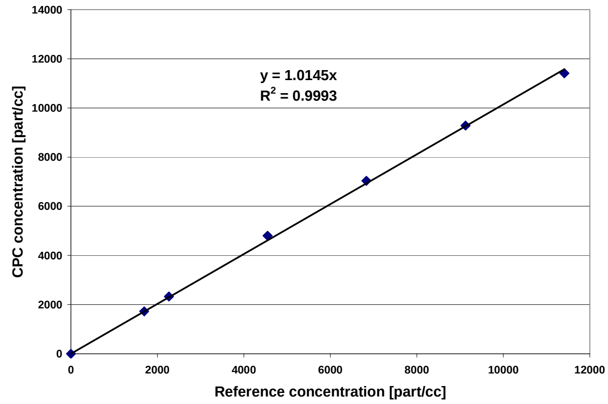

Fig 4. Daily linearity check for the CPC

The CPC in the SPCS shows good linearity and R-square value. The automated function for the CPC linearity check makes the calibration process much more efficient, accurate, and flexible. Range of concentrations from the DCU could be either uniform or non-uniform for the CPC. The R^2 value was greater than 0.95 which has cleared the PMP recommendation.

3.2 Removal Efficiency on Evaporation Unit

Evaporation unit (EU) has been integrated in the SPCS to remove SOF and sulfur compounds from the aerosol. To ensure removal of all SOF and sulfur compound particles, PMP recommended that the removal efficiency on Evaporation unit (EU) should be higher than 99% for 30 nm Tetracontan (C40) particles. Equation 4 shows the definition of the removal efficiency (RE).

$$RE = \{1 - C*DR_2/C_{up}\}*100 \quad (4)$$

Where, C is the concentration downstream of the PND_2; Dr_{PND2} is the dilution ratio on PND_2; C_{up} is the concentration into the EU.

A C40 generator was used to generate C40 particles. Then C40 particles moved into a DMA. Single size particles are selected by applying suitable voltage on the DMA. Then the aerosol enters the EU. When the aerosol flowed through the upstream of the EU, the raw concentration of the mono-disperse C40 was measured in a CPC. When the aerosol moved through the EU following the cold diluter, the concentration from the EU and diluted by the PND_2 was measured. The remove efficiency of the EU is calculated from the upstream and downstream concentrations.

Figure 5 presents 100 nm C40 particles upstream and downstream of the EU and PND_2. The temperature controller on the EU controls the temperature at 320 ºC. The concentrations from the upstream and downstream were measured and recorded for three minutes. Extremely low concentration of C40 particles was detected occasionally downstream of the PND_2. Removal efficiencies for 100 nm C40 particles are over 99%. It demonstrates the EU achieves the PMP recommendation and the SPCS design specification.

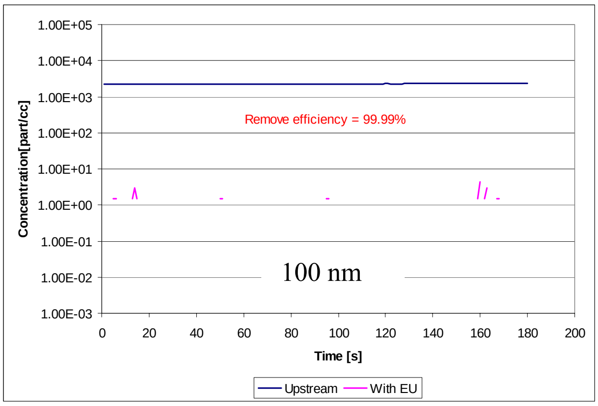

Fig 5. 100 nm C40 particle concentration upstream and downstream of the EU and PND2 (RE = 99.99%)

3.3 Penetration of Particles

The particle penetration on dilution system strongly influences the performance of an instrument. PMP draft regulation recommends the overall penetration on solid particles of diameters 30, 50, and 100 nm be ≥ 90%. To ensure the diluter with the best performance used on the SPCS, penetrations on SPCS and WRCD have been evaluated. The daily linearity check system was used in this case with minor modifications. The particle penetration is defined as:

$$P = DR * C_{down} / C_{up} * 100 \quad (5)$$

Where, DR is the total dilution ratio on the SPCS, C_{down} is the average concentration downstream of the diluter, and C_{up} is the average particle concentration upstream of the diluter.

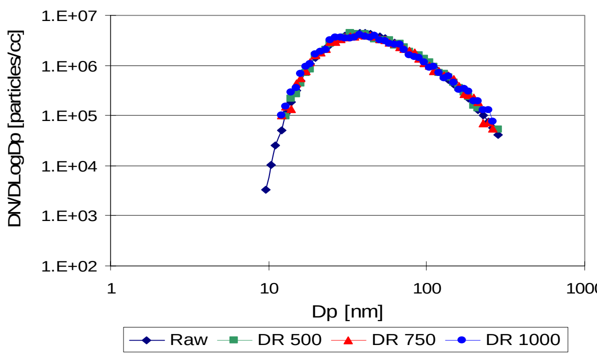

Fig 6. Size distributions on the SPCS

Figure 6 represents the size distributions of raw and diluted polydisperse NaCl aerosol. Diluted size distributions are corrected back to raw concentrations by multiplying the SPCS overall dilution ratios. Similar diluted size distributions are obtained on the SPCS with high dilution ratios. From the overall side distribution the total number of particles was calculated at upstream and downstream of the SPCS. It was found that about 97% particles penetrate through the SPCS which is sufficiently higher than the PMP recommendation.

3.4 Dilution Ratio on the SPCS

The accuracy of the dilution ratio of any measuring system strongly influences the accuracy of the number measurement. PMP suggests the dilution ratio should be calibrated with a well calibrated gas analyzer. The difference between gas analyzer and the diluter should be in ± 10%.

Dilution ratios on the SPCS were calibrated. Propane (C_3H_8) was used as the span gas in the calibration. The SPCS was run at the normal measurement conditions, the same as those described above. The dilution ratio measured by the HC analyzer (FID). The overall dilution ratio for the SPCS is expressed in the following equations.

$$DR_{HC} = 3 * C_{prop} / (C_{ana} - C_{bg})$$

$$DR_{SPCS} = DR_1 * DR_2 \quad (6)$$

Where, DR_{HC} is the dilution ratio calculated from the HC analyzer, C_{prop} is the concentration of the span gas in ppm, C_{ana} is the concentration measured with the HC analyzer in ppm, and C_{bg} is the HC background concentration in dilution air.

Figure 7 shows the comparison of the dilution ratios from the SPCS and those calculated from the gas measurement. The linear trend line is used to fit the curve. The R-square value obtained from the SPCS is 0.9967. Thus, the SPCS dilution ratio matches well to the dilution ratio from the gas measurement.

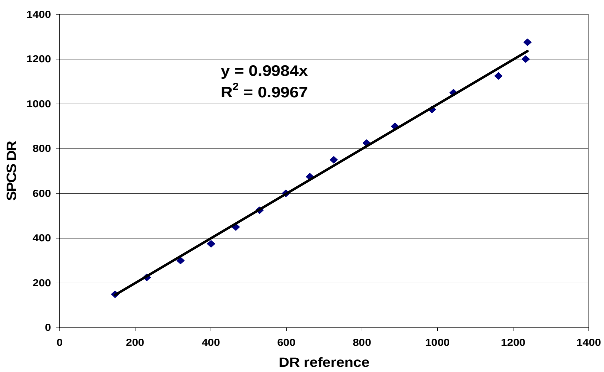

Fig 7. Dilution ratio calibration on the SPCS

Figure 8 presents the percentage difference between the SPCS dilution ratios and the gas dilution ratios obtained from different tests. The maximum difference obtained is +/-6% in worst cases. In general, the SPCS dilution ratios are in ± 4% difference with those obtained from the gas measurement. However the SPCS could clear the PMP recommendation easily.

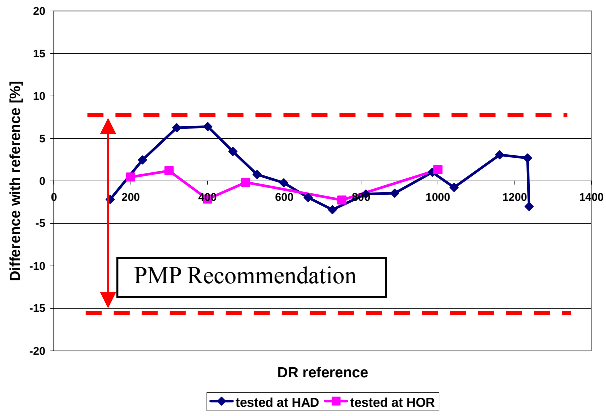

Fig 8. Percentage difference of the SPCS dilution ratio

3.5 Transient Test with Vehicle

Performance of the SPCS was tested with a diesel passenger car on a chassis dynamo cell. The car was a 1998 VW beetle having 1.8 l turbocharged diesel engine. A diesel oxidation catalyst (DOC) is installed on the vehicle exhaust system for HC and CO reduction. The certified fuel was used to run all tests. The vehicle was driven under European NEDC driving cycle. Sample was taken from the exit of a CVS full dilution tunnel after classifying the particles by a pre-classifier [6]. Since the robot driver needs to spend at least one day to set up and learn to drive the vehicle, the test cell technician drove the car in all tests.

Figure 9 shows the solid particle emission for NEDC in three continuous days. Large amount of solid particles are observed from the last cycle on NEDC test, where the vehicle speed achieves 120 km/h. Good repeatability has been observed from the test. Table 1 shows the summary of the diesel vehicle test in three continuous days.

Table 1: Solid particle emission from VW beetle

Test No.	Test Mode	Distance (km)	Total SPCS DR	Emission (#/km)	Difference (%)
Day I	NEDC	11.050	1250	4.837E+13	0.00
Day II		10.982		4.898E+13	-1.26
Day III		11.005		4.833E+13	0.09

3.6 Transient Test on Engine Bench

Finally the performance of the SPCS was tested in an engine fitted with DPNR system. The test was done in an engine bench running the engine on JE-05 driving mode. The engine is a four cylinder DI diesel with cooled EGR and common rail injections system. Production year 2003 and it cleared the Japan 2002 emission regulation. The fuel is commercial diesel with less than 10 ppm sulfur.

Sample was drawn directly from the exhaust pipe in both cases before and after the DPNR well before the dilution tunnel [7]. However to avoid higher concentrations of particles only an ejector type diluter (single stage) was used before the SPCS. The dilution ratio of the ejector diluter was kept low at 8 and dilution

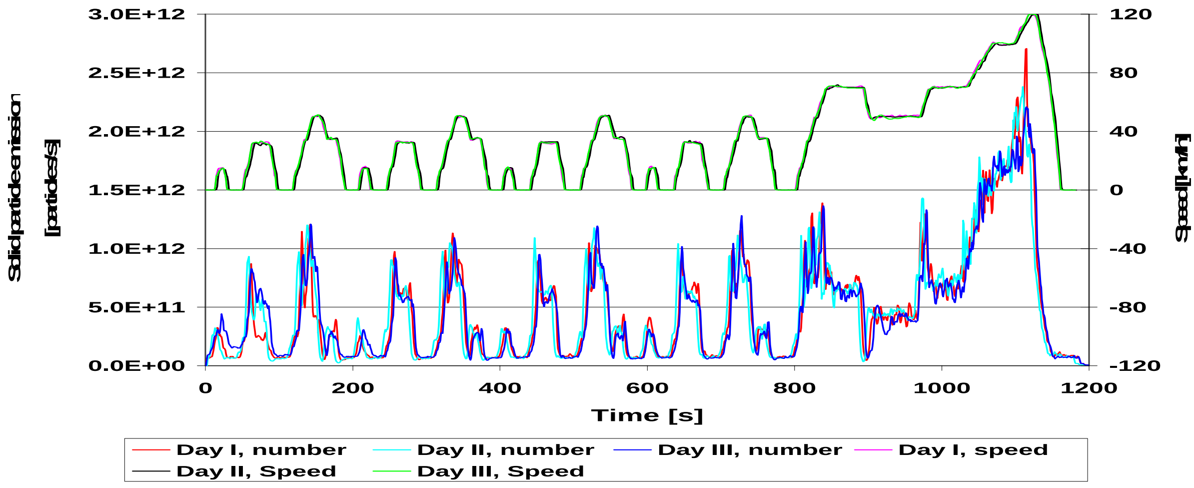

Fig 9. Solid particle emission for NEDC from the diesel vehicle

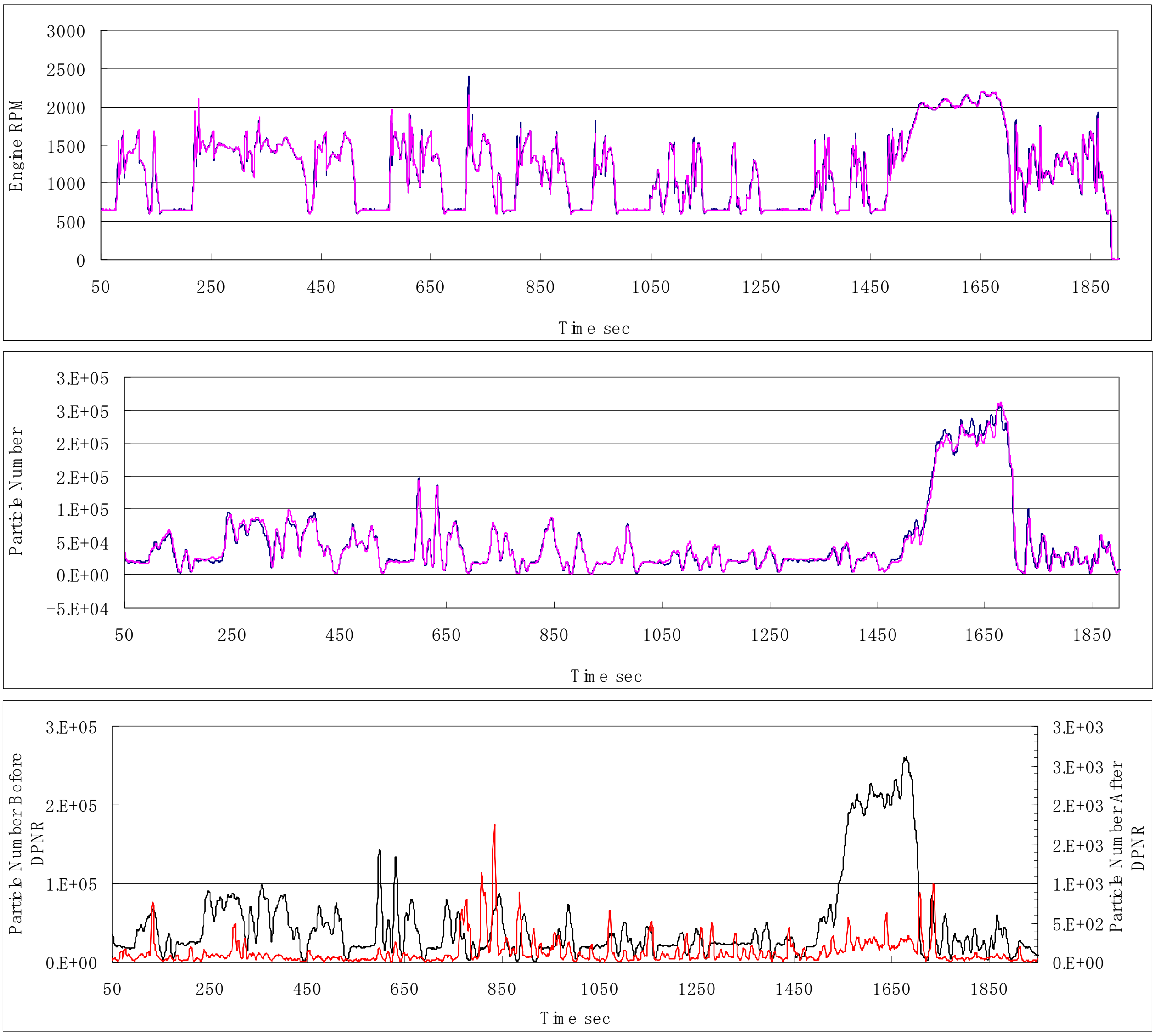

Fig 10. Solid particle emission for diesel engine under JE05 mode

temperature was 150C. The diluter was also used after the DPNR to keep similarity in sampling condition [8, 9]. There was no significant variation in the DR even the exhaust pipe pressure fluctuated vigorously. The fluctuation was almost minimized by the single stage ejector diluter.

Figure 10 shows the concentration of particles before DPNR and that of after DPNR. The data presented in the figures are not corrected by this dilution ration. Before the DPNR the SPCS shows excellent repeatability and sensitiveness to the driving condition. It was confirmed from the data after DPNR that the DPNR can remove about 99% of the diesel PM. As a whole the SPCS can be used to test the performance of DPF/DPNR systems.

4. CONCLUSIONS

European PMP proposed a draft regulation for Light-duty diesel vehicle solid particle measurement. This draft regulation gives recommendations on the design of the measuring system. Horiba developed the solid particle counting system (SPCS) according to PMP recommendation. The performance of the instrument has been evaluated. Some of the performance results are presented in this paper. The following conclusions were obtained from the above discussion:

- The SPCS shows good penetration for solid particles. Penetrations higher than 95% on the SPCS are above the minimum penetration, 90%, recommended by PMP.
- Dilution ratios on the SPCS present normally ± 4% difference to those obtained from well calibrated gas analyzers. The accuracy is much better than the minimum recommended by the PMP, which is ± 10%.
- Performance of the SPCS is consistent. Similar and repeatable results have been obtained.
- Many functions, such as normal measurement, zero checks for CPC and the system, flow check for CPC, daily linearity check for CPC, data saving, etc., have been automated. The instrument is easy to operate.
- Two PID loops have been integrated in the SPCS. They keep the dilution ratios on the SPCS unchanged when the sample condition is changed. Thus, the instrument isn't sensitive to the sample condition. It is good for steady-state and transient tests.
- The dilution ratio is accurate over the whole designed range, and doesn't decrease while the dilution ratio increases. Penetrations on the WRCD are much higher than those tested on ejector diluters and rotary diluters. Real-time dilution ratios are available from the diluter. It is an idea diluter for the SPCS.

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